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SPALL BEHAVIOR AND DAMAGE EVOLUTION IN TANTALUM

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We conducted a number of plate impact experiments using an 80-mm launcher to study dynamic void initiation, linkup, and spall in tantalum. The tests ranged in shock pressure so that the transition from void initiation, incipient spall, and full spall could be studied. Wave profiles were measured using a velocity interferometry system (VISAR), and targets were recovered using "soft" recovery techniques. We utilized scanning electron microscopy, metallographic cross-sections, and plateau etching to obtain quantitative information concerning damage evolution in tantalum under spall conditions. The data (wave profiles and micrographs) are analyzed in terms of a new theory and model of dynamic damage cluster growth. We have developed a model of ductile damage based on void coalescence of initially nucleated voids, that leads to clusters of voids. At low loading strain rates, the biggest cluster has time to grow much more rapidly than smaller clusters to break the sample. At high loading strain rates, large clusters cannot grow any faster than smaller clusters so the sample breaks when enough clusters grow independently to form a fracture surface by random accumulation.

Material and Experiment Description

In this study we used commercially-pure (triple-electron-beam, arc melted) unalloyed tantalum plate with the measured composition (in wt. %) of carbon-6 ppm, nitrogen-24 ppm, oxygen-56 ppm, hydrogen- <1 ppm, iron-19 ppm, nickel-25 ppm, chromium-9 ppm, tungsten-41 ppm, niobium-26 ppm and balance tantalum. The tantalum plate was in an annealed condition and had an equiaxed grain structure of 68 μm grain size [1]. We performed the uniaxial strain spall tests utilizing an 80-mm single-stage launcher and recovery techniques as described previously [2]. Tantalum samples were spalled at 9.5 and 17 GPa pulse pressure and 1 μs pulse duration under symmetric impact conditions. Recovered spalled samples were analyzed using optical and scanning electron microscopes.

Previous, recovery and non-recovery spall tests reported 5.2 GPa spall strength for 6 GPa shock amplitude, 7.3 GPa spall strength for 9.5 GPa shock amplitude, and 3.0 to 4.5 GPa spall strength for 15 GPa shock amplitude [1, 3, 4].

Results and Discussion

In this experiment we were particularly interested in the dynamic void initiation, void linkup and fracture by spall. Therefore, we have chosen the applied pulse pressure to either fully spall the sample or to introduce the spall surface but not to allow the surfaces to fully separate creating so called incipient spall. A typical VISAR spall trace is presented in Figure 1.

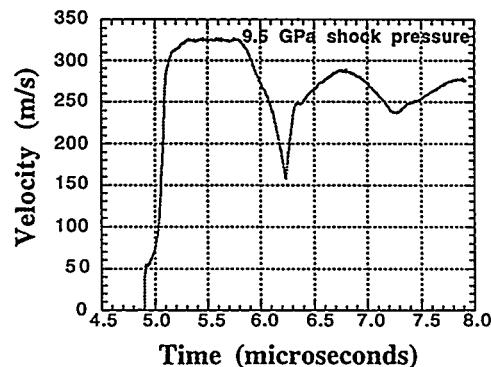


Figure 1. VISAR spall trace of tantalum spalled at 9.5 GPa.

The spall test at 9.5 GPa pulse pressure produced an incipient spall fracture. The cross section of the recovered spall sample showed a distinctive cracks running across the entire diameter of the sample with multiple branched and interlocking cracks extending into the sample away from the principal fracture surface. The two halves of the spall sample did not separate from each other, regardless of the fact that the pulse pressure exceeded the expected spall strength of this material. Figure 2 shows the optical micrograph of the cross section of the tantalum sample spalled at 9.5 GPa shock pressure. We have sectioned off part of the spalled sample to allow it to separate the spall surfaces. Figure 3 shows the typical ductile dimple fracture surface characteristic for metals in Group V_A. Multiple impurities on the fracture surface are present, and most likely they are responsible for the voids initiation.

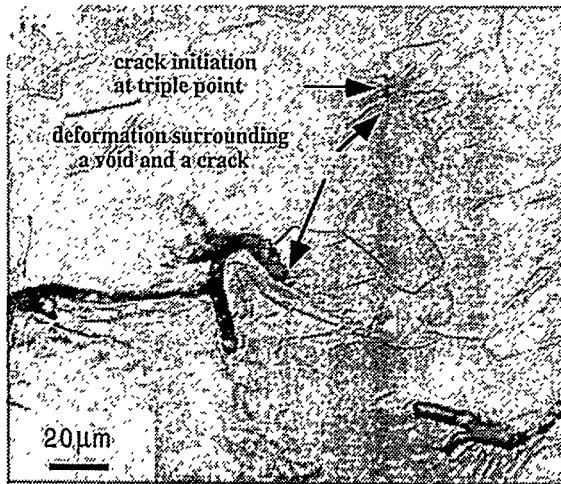


Figure 2. Cross section of tantalum sample spalled at 9.5 GPa showing void initiation at point of intersection of several grains and propagating cracks with deformation surrounding a void and a crack.

Under increased loading pulse pressure (17 GPa), the spall was complete and two halves of the spalled sample fully separated to reveal fracture surface. Scanning electron microscope pictures of the fractured surfaces showed a mixture of ductile dimple and cleavage fracture (Figure 4).

This change in the fracture morphology can be induced by the significant deformation twinning which will initiate cleavage [1]. The etched cross section, orthogonal to the spall fracture surface,

reveals significant density of deformation twins and only few twins in the sample spalled at lower pulse pressure (compare Figure 2 with Figure 5).

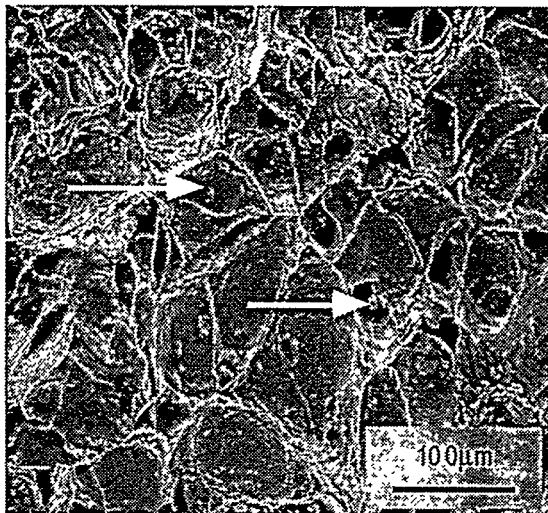


Figure 3. Spall fracture surface of tantalum spalled at 9.5 GPa. Arrows point to the particles which most likely initiated dimples on a ductile fracture surface.

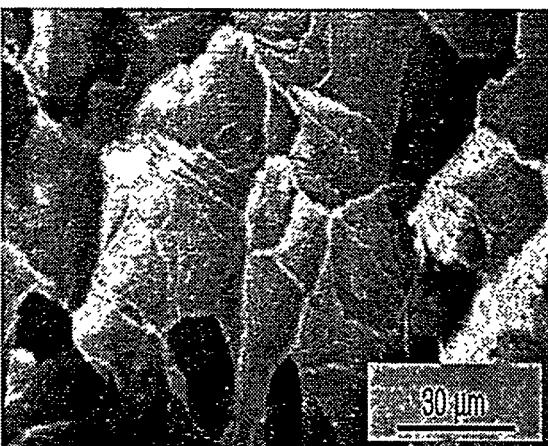


Figure 4. Fracture surface of tantalum spalled at 17 GPa shock pressure. The micrograph shows a mixture of cleavage fracture and ductile dimples present on the fracture surface.

In contrast, to the sample tested at the lower pulse amplitude, the crack branching is not so pronounced. This, and the change in mode fracture from ductile to mixture of ductile and cleavage fracture explains an observed decrease in spall strength with increased applied pulse amplitude in this material [1,3,4].

Under severe loading rates or low temperatures the cleavage fracture is

associated with the ductile-to-brittle transition in this material [1, 5].

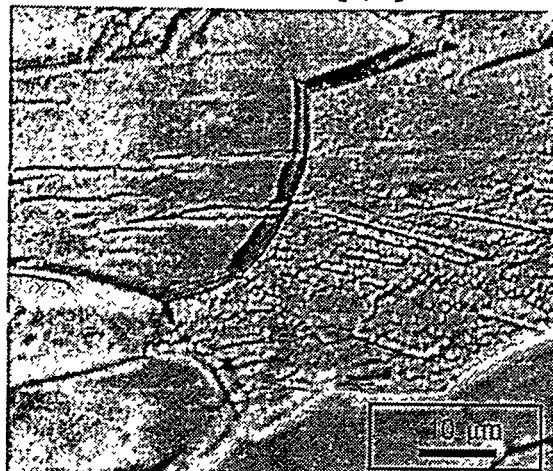


Figure 5. Deformation twins present on the cross section of the tantalum sample spalled at 17 GPa shock pressure.

With an increase in an applied stress, high hydrostatic tensile stress develop at the spall plane, and the stress at which the ductile-to-brittle transition occurs is pushed to the higher temperature since fracture stress is in the first approximation linearly proportional to the applied stress. The combination of this effect and significant amount of deformation twinning triggers cleavage fracture. It would be interesting to investigate the susceptibility of different fracture modes to the impurity levels, since these could impinge the dislocation motion and influence dislocation storage and twins interaction in this material.

A theoretical program is underway to model the damage evolution observed in materials such as tantalum. The model includes damage induced by shear stress as well as damage caused by volumetric tension. Spallation is included in the model as a special case and strain induced damage is also treated. Void nucleation and growth are taken into account, and give rise to strain rate effects through elastic release wave propagation between damage centers (voids). The underlying physics of the model is the nucleation, growth, and coalescence of voids in a plastically flowing solid. The model is intended for hydrocode based computer simulation. The details of the model are published elsewhere [6].

Conclusions

We studied damage evolution in tantalum

under the spall conditions for impact stresses of 9.5 and 17 GPa. The lower shock pressure amplitude (9.5 GPa) formed an incipient spall with the ductile fracture characteristics and cracks in a primary spall plane and cracks extending over several tens of microns in the direction of wave propagation. At high shock pressure the spall was complete and we observed a mixed (ductile and cleavage) fracture mode. Cross sections of the spall surfaces reviled twinning for the high pressure spall case and no twinning in the low pressure case. A theoretical program is underway to model the damage evolution observed in tantalum.

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